PB-217 678

RATIONALE FOR A MATERIAL SPECIFICATION FOR COMMERCIAL FILTER AIDS FOR MILITARY USE

Charles S. Oulman, et al

Iowa State University
Ames, Iowa

August 1968

DISTRIBUTED BY:

NTIS

National Technical Information Service
U. S. DEPARTMENT OF COMMERCE
5285 Port Royal Road, Springfield Va. 22151

WP-00196

PB 217 678

ENGINEERING
RESEARCH
INSTITUTE

IOWA STATE
UNIVERSITY
AMES, IOWA

Reproduced by
NATIONAL TECHNICAL
INFORMATION SERVICE
U S Department of Commerce
Springfield VA 22151

ENGINEERING RESEARCH

ENGINEERING RESEARCH
ENGINEERING RESEARCH
ENGINEERING RESEARCH
ENGINEERING RESEARCH

FINAL REPORT
PART III OF VI PARTS

RATIONALE FOR A MATERIAL SPECIFICATION FOR COMMERCIAL FILTER AIDS FOR MILITARY USE

Charles S. Oulman
Associate Professor of Civil Engineering

E. Robert Baumann
Professor of Civil Engineering

Submitted to:
U.S. Army Engineer Research and Development Laboratories
(Contract DAAK02-67-C-0408)
Fort Belvoir, Virginia

ERI-268
Project No. 684-S

August 1968

SANITARY ENGINEERING SECTION
ENGINEERING RESEARCH INSTITUTE
IOWA STATE UNIVERSITY AMES

CONTENTS

	Page
INTRODUCTION	1
APPROACH USED IN STUDY	6
TEST RESULTS	10
Filtration Tests	10
Physical Characteristics Tests	12
TEST RESULTS INTERPRETATION	15
Particle Size	15
Filter Cake Resistance with Suspended Solids	20
Filter Aid Index	28
Proposed Filter Aid Specification	35
CONCLUSIONS AND RECOMMENDATIONS	38
ACKNOWLEDGMENTS	39
REFERENCES	40
APPENDIX	41

FIGURES

		Page
Fig. 1.	Filter cake resistance, β, for 11 filter aids at the 95% confidence level at values of C_S/C_F of 0.02, 0.05, and 0.10.	11
Fig. 2.	Typical particle size distribution and two idealized particle size distributions for filter aids having the same effective size.	17
Fig. 3.	Nomograph for calculating porosity based on the equation: $f = (1 - \gamma_F/\gamma_W\rho_F)$.	19
Fig. 4.	Nomograph for calculating effective particle size (D_{em}) based on the equation: $D_{em} = \frac{1794\ (\gamma_W/\gamma_F\rho_F)^{\frac{1}{2}}}{f^2}$.	19
Fig. 5.	Limiting values of β, using J0, lot 1.	22
Fig. 6.	Average relation of β and (C_S/C_F) values for 11 filter aids evaluated in this study.	23
Fig. 7.	Relation of k value to effective particle size of filter aids used in this study.	26
Fig. 8.	Relation of k value to hydraulic radius of filter aids used in this study.	31
Fig. 9.	Nomograph for calculating the filter aid index (I) based on the equation: $I = \gamma_F^{3/2}\beta_o^{1/2}/\rho_F$.	33

TABLES

		Page
Table 1.	Body feed requirements to give "equivalent performance" using eleven grades of filter aid.	12
Table 2.	Average physical properties of the eleven grades of perlite and diatomite filter aids included in this study.	14
Table 3.	Comparative values of β_0 resulting from constant-rate and constant-pressure filtration.	14
Table 4.	β_0 values for filter aids having a straight line, particle size distribution for uniformity coefficients ranging from 1.0 to 6.0.	18
Table 5.	Average values of the effective size of the filter aids evaluated in this study.	20
Table 6.	Summary of filtration test results for filter aid J0, lot 1.	21
Table 7.	Prediction of body feed requirements for "equivalent performance."	28
Table 8.	Filter aid index (I) and body feed requirement predictions for "equivalent performance" for the eleven grades of filter aid tested in this study.	34
Table 9.	Ratings for 36 filter aid lots on the basis of a filter aid index (I) of 13400 $\pm$ 3000 and an effective size (D_{em}) of 12.4 $\pm$ 6.0μ.	36

SYMBOLS

A_p = particle surface area, $[L^2]$ or ft^2

C_D = drag coefficient, [−]*

C_F = body feed concentration, $[F/10^6F]$ or ppm

C_S = suspended solids concentration, $[F/10^6F]$ or ppm

D = particle diameter, [L] or ft

D_{10} = effective particle size, [L], ft or microns

D_{50} = mean particle size, [L], ft or microns

D_{60}/D_{10} = uniformity coefficient, [L/L]

D_e = effective size based on permeameter test, [L] or ft

D_{em} = effective size based on permeameter test, [L] in microns

H = headloss, total through filter, [L] or ft

H_c = headloss, through filter cake, [L] or ft

H_p = headloss, through precoat layer, [L] or ft

H_s = headloss, through filter septum, [L] or ft

I = filter aid index, $[F^{3/2}L^{-11/2}]$

K = proportionality constant, [−]

L = filter cake thickness, [L] or ft

N_{re} = Reynolds number, [−]

R = hydraulic radius, [L] or ft

R_e = hydraulic radius based on permeameter test, [L] or ft

R_{em} = hydraulic radius based on permeameter test, [L] in microns

V_F = body feed requirement on a volumetric basis, $[L^3/7.48 \times 10^6L^3]$ or cu ft/MG

V_p = particle volume, $[L^3]$ or cu ft

---

*Dimensionless units.

V_U = volume of voids per unit weight of filter aid, $[L^3/F]$ or cu ft/lb

V_V = volume of voids in filter cake, $[L^3/10^6F]$ or cu ft/10^6 lb

X = weight fraction of particles in a given size range, [−]

a = exponent (a constant), [−]

b = exponent (a constant), [−]

f = porosity or void ratio, $[L^3/L^3]$ or [−]

g = gravitational constant, $[LT^{-2}]$ or 32.2 ft/sec^2

k = constant depending on the kind of suspended solid removed by filtration, $[LF^{-1}]$ or ft/lb

q = rate of flow, $[LT^{-1}]$ or cfs/ft^2

t = time, [T] or sec

α = filter cake resistance index, $[L^{-2}]$ or ft^{-2}

β = filter cake resistance, $[L^{-2}]$ or ft^{-2}

β_o = filter cake resistance of clean filter aid, $[L^{-2}]$ or ft^{-2}

γ_F = bulk density of filter aid, $[FL^{-3}]$ or pcf

γ_W = density of water, $[FL^{-3}]$ or pcf

μ = dynamic viscosity, $[FTL^{-2}]$ or lb-sec/ft^2

ρ_F = effective specific gravity, $[FL^{-3}/FL^{-3}]$ or [−]

ϕ = a shape factor, [−]

INTRODUCTION

Diatomite and perlite filter aids are used to increase the filtrability of water that contains suspended solids. Filter cakes containing the appropriate grade of either diatomite or perlite filter aids will entrap suspended solids too small to be removed by sand filters and will accomplish this removal without building up an excessively high headloss.

In considering the purchase of filter aids, two or more may be assumed equivalent when they provide the same quality of filtered water with the same filter cake resistance. The quality of water produced by the different types and grades of filter aids available is influenced by the characteristics of the suspended solids to be removed and by the characteristics of the filter aid used in filtration. The quality of the filtered water improves with the use of finer and finer grades of filter aid, but the filter cake resistance increases when equal weights of the finer filter aids are used as body feed. In practice, it is customary to use the coarsest grade of filter aid that will provide the desired filtered water quality and to adjust the body feed to obtain the desired level of filter cake resistance.

Once a grade of filter aid is selected for a given filtration application, it is frequently necessary to establish its characteristics so that a purchase specification can be written. The specification should be written so that other grades of the same or different materials may be considered for purchase if they provide "equivalent performance." Thus, "equivalent performance" implies that filtration with the equivalent filter aids provides the same quality of filtered water with the same filter cake resistance. Such performance with the same type of material,

for example, can be obtained by using finer grades of filter aid by increasing the rate of body feed. These finer grades of a filter aid are usually slightly cheaper than the coarser grades. The use of increased amounts of finer grades as body feed may provide economical "equivalent performance," if the cost of purchasing and shipping a greater amount of material to the point of use is not excessive.

The specification adopted may be either a performance specification or a material specification. The performance specification delineates the conditions under which the material purchased will be used and sets forth the results that are expected. The test of whether a material meets the performance specification is whether it produces the desired quality of water with the specified rate of headloss buildup or less at the point of use under actual operating conditions.

The material specification describes the material desired in terms of physical properties needed to achieve the desired performance. Standardized laboratory tests can then be used to determine whether the material in question has the specified properties. One of the problems inherent in the use of a material specification lies in determining how much of a finer filter aid is required to provide resistance equivalent to that of a given amount of coarser filter aid, so that the cost of using the finer material can be compared with that of the coarser material. The physical properties described in a material specification must be measureable with enough accuracy that the expected performance of the filter aid can be predicted with accuracy.

In any event, it is necessary that the buyer must know or be able to determine the performance that he wishes to achieve. A filter aid can

then be selected on the basis of a performance test and be described in terms of a material specification. Alternate filter aids can then be evaluated in terms of whether they can be expected to provide equivalent performance.

The filtration performance of a filter medium is a function of many variables, some of which are physical characteristics of the medium itself. Physical characteristics of the medium that are important include particle size and shape and the volume of the voids in the cake as it is formed on a filter septum for use in filtration.

A particle size analysis of a filter aid can be made using a variety of methods including the hydrometer method, the Coulter counter method, and the permeameter method. The results of the various methods will not necessarily agree unless the particles are spherical. Any of the methods can be used for determining the particle size of diatomite, but the hydrometer method cannot be used with perlite because of the variable specific gravity of the particles in this type of filter aid. The permeameter method is particularly appropriate for use with both diatomite and perlite filter aids, because the same test used for determining the filter aid resistance, β_0, $[L^{-2}]$, is used for determining the bulk density. Thus, bulk density and particle size can be determined under the same test conditions.

To determine the volume of voids in a filter cake, it is necessary to determine both the effective specific gravity of the media and the bulk density of the filter aid as it exists in a filter cake. The effective specific gravity of the filter media, ρ_F, is defined as the ratio of the weight of a unit volume of filter aid to the weight of an equal volume of

water at 20°C and is expressed in dimensionless terms. The bulk density of the filter media, γ_F, is defined as the weight of the filter media per unit volume of a filter cake as it would be formed in filtration (without other suspended solids present). The bulk density of the filter media is usually expressed in the units pounds per cubic foot.

The bulk density, effective specific gravity, and void volume of filter media are related as expressed in the following equation:

$$f = \text{void ratio} = \frac{\text{volume of voids in filter cake}}{\text{volume of filter cake}} = \frac{\gamma_w - (\gamma_F/\rho_F)}{\gamma_w}$$

$$= 1 - \frac{\gamma_F}{\gamma_w \rho_F} \qquad (1)$$

where γ_F = bulk density of filter aid, $[FL^{-3}]$

γ_W = density of water, $[FL^{-3}]$

ρ_F = effective specific gravity of filter media, $[FL^{-3}/FL^{-3}]$ or $[-]$*.

In order to determine how much of each potentially equivalent grade of filter aid is required to provide the same filtration resistance, an equation was developed to relate the physical characteristics of a filter aid to the resistance of the filter cake formed during filtration. This equation is in the following form:

$$\alpha = \frac{k}{V_v} \qquad (2)$$

where α = filter cake resistance index, $[L^{-2}]$

k = constant depending on the suspended solid removed by filtration, $[LF^{-1}]$ or ft/lb

---

*[−] Dimensionless units.

V_v = volume of voids in the filter cake = $\frac{C_F}{\gamma_F}\left(1 - \frac{\gamma_F}{\gamma\ \rho_F}\right)$,
cu ft per 10^6 lb of filtrate, $[L^3F^{-1}]$

C_F = body feed concentration, ppm by weight $[F/10^6F]$.

In filtration of an iron-bearing water used to simulate the operation of an Erdlator[1], Part I, the constant k in Eq. (2) was found to be a function of the effective particle size of the filter aids. A different k value – particle size relationship was found for the filter aids from each manufacturer.

In order to determine the amount of body feed using any other grades of filter aids needed to provide equivalent performance, it is necessary to be able to determine average values for the following characteristics for each filter aid:

- specific gravity of the filter aid, ρ_F,
- bulk density of the filter aid, γ_F, and a,
- filter aid resistance index, or the β_o-index.

APPROACH USED IN STUDY

The purpose of water filtration is the separation of suspended solids from water. The objective of this investigation was to determine the principal characteristics of filter aids that must be specified when comparing their relative effectiveness for removing suspended solids from water.

Many commercial filter aids from different production lots were evaluated in this study. To identify the filter aids by manufacturer, grade, and source or production lot, a special coding system was developed. In the coding system (J4-16, for example), a letter (J, for example) was used to designate the manufacturer of the filter aid. A number (4, for example) immediately following the letter designates the filter aid grade. The source or production lot of the sample (-16 in the example) was designated by a second number separated from the manufacturer and grade designation by a hyphen. Filter aids S2, S3, and S4 are perlite filter aids; J4, J3, J0, E6, E5, E2, G4, and G1 are diatomite filter aids.

The filter aid best suited for use in a given filtration application is the one producing the desired quality of water and the desired filter operating characteristics at the lowest overall cost. For an existing filter plant, the lowest overall filter aid cost depends on the cost of the filter aid used as precoat and on the cost of the body feed needed to give the desired length of filter run. It is, therefore, necessary to be able to predict the filter cake resistance which would be obtained using any filter aid that might be offered as "equal to or better than" a specified grade of filter aid which is known to be satisfactory.

The headloss which builds up across a filter during a filter run is caused by a combination of three resistances:

- The resistance of the filter septum which supports the filter media,
- The resistance of the "precoat" layer of clean filter aid deposited on the septum to prevent suspended solids from penetrating into or through the septum,
- The resistance of the filter cake formed as suspended solids and body feed filter aid are removed on the precoat layer.

The headloss may be expressed by the equation:

$$H = H_s + H_p + H_c \tag{3}$$

where H = total headloss through the filter, [L] or ft

H_s = headloss through the filter septum, [L] or ft

H_p = headloss through the precoat layer, [L] or ft

H_c = headloss through the filter cake, [L] or ft.

The headloss across the filter cake at any given time during a filter run is a function of the rate of flow, the viscosity of the water being filtered, the concentration of filter aid being used as a body feed and a resistance characteristic of the body feed-suspended solids filter cake that is formed.

$$H_c = \frac{q^2 t \mu \beta C_F}{\gamma_W} \text{ (for flat septa)} \tag{4}$$

where q = rate of flow, $[LT^{-1}]$ or cfs/ft^2

t = time, [T] or sec

μ = dynamic viscosity, $[FTL^{-2}]$ or $lb\text{-}sec/ft^2$

γ_w = specific weight of water, $[FL^{-3}]$ or lb/ft^3

β = filter cake resistance, $[L^{-2}]$ or ft^{-2}

C_F = body feed concentration, $[F/10^6F]$ or ppm.

The filter cake resistance represented by the resistance index, β, is determined from the results of a constant-rate filter run in which the rate of build up of headloss is determined during the filtration of the water containing a given concentration of suspended solids, C_S, and a concentration of body feed, C_F, which is held constant[1,Part V].

To compare the filtration performance of competitive grades of filter aids, a standard water of uniform quality was filtered in a large number of filter runs (over 300) using 42 different lots of 11 different filter aids[1,Part I]. The test results were used to evaluate the filter cake resistance obtained using the different grades and types of filter aid. The standard water, containing about 8 ppm of iron, was prepared by precipitating hydrated ferric oxide from a solution of ferric chloride. Eleven grades of filter aid from four different manufacturers were evaluated; each could produce the desired quality of filtered water. The effluent concentration of iron in all filter runs was less than 0.06 ppm regardless of the grade of filter aid used when the body feed concentrations were held between about 50 to 500 ppm. At least five filter runs were made using each of at least three different lots of each grade of filter aid.

In addition to their filtration characteristics, four physical properties of each filter aid were determined to characterize the filter aids[1,Part II]. These properties were:

- effective specific gravity (ρ_p), $[FL^{-3}/FL^{-3}]$ or [−]*

---

*[−] Dimensionless units.

- bulk density as found in a filter cake (γ_F), $[FL^{-3}]$ or lb/ft^3
- filter cake resistance of the precoat filter cake (β_o), $[L^{-2}]$ or ft^{-2}
- particle size distribution.

An inherent objective of the study of the physical characteristics of filter aids was to develop simple standard procedures to determine these physical characteristics[1,Part IV].

The overall study of Filter Aid Specifications was conducted to develop a method for writing a single performance or material specification that would be applicable for the purchase of commercial filter aids for military use. Such a specification, to be useful, has to be based on measurements of filter aid properties which are related to filtration performance and which can be made using standardized procedures and apparatus to provide reproducible and accurate results when performed by different technicians in different locations. The filtration and physical characteristics studies were conducted so that the relationship between the physical characteristics and the filtration characteristics of the filter aids could be compared to establish which of the physical characteristics are important in filtration. It was hoped that these studies would provide the data necessary for developing a quantitative relationship between the filtration characteristics and the significant physical characteristics in a form useful in establishing a material specification for filter aids. This portion of the final report describes the rationale for such a material specification for commercial filter aids for military use.

TEST RESULTS

Filtration Tests

The filtration tests yielded results that can be presented in a number of ways. Figure 1 shows the filter cake resistance, β, observed using the eleven filter aids at C_S/C_F ratios of 0.02, 0.05, and 0.10. The dotted lines indicate the range of values determined in the tests and the cross-hatched area shows the 95% confidence interval for each filter aid.

To provide "equivalent performance" in a filter run, the body feeds using different filter aids must be adjusted to provide equal values of βC_F. The body feed requirements for "equivalent performance" for a filter run lasting 6 hr with a terminal headloss of 100 ft at a flow rate of 1 gpm per sq ft while filtering a water containing 4 ppm of iron at 68°F are shown in Table 1[1,Part I].

Based on these results, the filter aids can be grouped so that those grades within the group have filter aid requirements not significantly different from the other filter aids in the same group. On a weight basis, the filter aids can be grouped as follows:

Group 1. S2	Group 4. E5, G4
Group 2. S3, S4, J4, J3	Group 5. E2, G1.
Group 3. J0, E6	

On a volumetric basis, the filter aids can be grouped as follows:

Group 1. J4	Group 3. E5, S3
Group 2. J3, E6, J0, G4, S2	Group 4. S4, E2, G1.

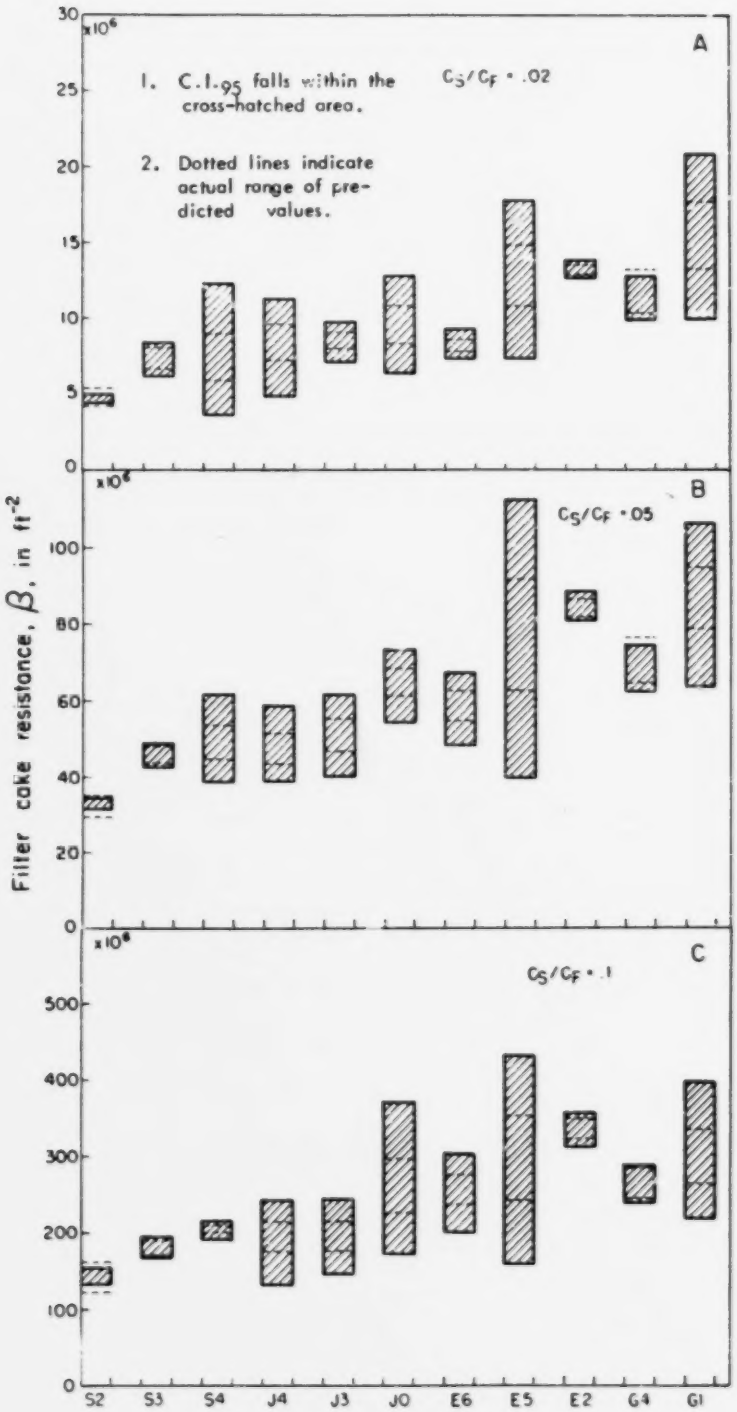
A
1. C.I.95 falls within the cross-hatched area.
2. Dotted lines indicate actual range of predicted values.
C_S/C_F = .02
B
C_S/C_F = .05
C
C_S/C_F = .1
x10⁶
Filter cake resistance, β, in ft⁻²
S2 S3 S4 J4 J3 J0 E6 E5 E2 G4 G1

Fig. 1. Filter cake resistance, β, for 11 filter aids at the 95% confidence level at values of C_S/C_F of 0.02, 0.05, and 0.10.

Table 1. Body feed requirements to give "equivalent performance"* using eleven grades of filter aid[1,Part I].

Filter aid grade	Body feed requirement	
	Weight basis lb/MG	Volume basis cu ft/MG
S2	633	59.7
S3	866	68.2
S4	933	71.7
J4	951	44.9
J3	983	50.3
J0	1174	55.7
E6	1041	53.5
E5	1483	62.6
E2	1574	74.6
G4	1349	56.8
G1	1891	83.4

*Based on a flow rate of 1 gpm/ft^2, a run length of 6 hr, a terminal headloss of 100 ft of water, a water containing 4 ppm of iron at 68°F, and flat septa.

Physical Characteristics Tests

Four different analytical methods were used in determining the physical properties of the filter aids tested in this study.

- Coulter Counter method – used to determine the particle size distribution of perlite filter aids. This method was not used for diatomite filter aids because the hydrometer method permitted the use of a larger, more representative sample.
- Hydrometer method – used to determine the particle size distribution of diatomite filter aids. This method could not be used with perlite filter aids because this material does not have a uniform particle specific gravity.
- Pycnometer method – used to determine the effective specific gravity of perlite and diatomite filter aids.
- Permeameter method – used to determine the bulk density and filter cake resistance of perlite and diatomite filter aids.

The results of these analyses are summarized in Table 2 which lists the average values of effective size (D_{10}), mean particle size (D_{50}), uniformity coefficient (D_{60}/D_{10}), effective specific gravity (ρ_F), bulk density (γ_F), and filter cake resistance (β_o) for each of the eleven grades of filter aid tested in this study.

The value of β_o was also determined for several filter aids in an actual constant-rate filtration run made using suspended solids free water to which only body feed was added. The study was made to determine whether the resistance of the filter aid measured using the standard test procedure was comparable to that observed in an actual filtration situation. The results, summarized in Table 3, are comparable.

Table 2. Average[(a)] physical properties of the eleven grades of perlite and diatomite filter aids included in this study[1], Part II.

Filter aid grade	D_{10}, μ	D_{50}, μ	D_{60}/D_{10}	ρ_F	γ_F pcf	β_o ft^{-2}
S2	10	28	3.3	1.6	9.9	4.2×10^5
S3	9	24	3.1	1.7	12.6	5.7×10^5
S4	9	24	3.1	2.0	13.0	6.5×10^5
J4	10	19	2.3	2.3	19.7	1.1×10^5
J3	7	16	2.7	2.3	19.9	1.2×10^5
J0	6	14	3.0	2.3	19.9	1.9×10^5
E6	11	24	2.6	2.2	19.3	0.7×10^5
E5	9	20	2.7	2.3	23.2	1.1×10^5
E2	8	16	2.1	2.3	20.7	1.6×10^5
G4	7	21	3.5	2.3	23.5	1.1×10^5
G1	5	14	3.5	2.3	22.3	2.3×10^5

(a) The average values reported above have been rounded off so as to indicate the relative precision of the values. Values for an individual lot used in computing the average were determined to at least one additional decimal place beyond the average value reported in the table.

Table 3. Comparative values of β_o resulting from constant-rate and constant-pressure filtration.

Filter aid grade	Lot number	Filter cake resistance (β_o), ft^{-2}	
		Constant rate	Constant pressure
D4	3	1.52×10^5	0.99×10^5
D4	4	1.53×10^5	1.15×10^5
E2	3	2.13×10^5	1.54×10^5

TEST RESULTS INTERPRETATION

Particle Size

According to Hazen[3], the resistance to the passage of water offered by a bed of sand within which the grains are distributed homogeneously remains the same regardless of size variations (up to a uniformity coefficient of about 5.0), provided that the effective size remains unchanged. The effective size is the diameter of the largest particle in that 10% of a sample, by weight, which contains the smallest grains. The uniformity coefficient is the ratio of the size of the largest grain in 60% of the sample, by weight, which contains the smallest grains to the effective size.

According to Hazen's observations, the value of β_o should be a function of the effective size, D_{10}, of the filter aid. This observation is the basis for using permeameter test results to determine the mean particle size of filter aids. Particle size can be determined using β_o. This is demonstrated using either the Carmen-Kozeny equation or the Rose equation[4]. According to the Rose equation, for example:

$$H_c = \left(\frac{1.067}{\Phi}\right)\left(\frac{C_D}{g}\right)(L)\left(\frac{q^2}{f^4}\right)\Sigma\frac{X}{D} \qquad (5)$$

where g = gravitational constant, $[LT^{-2}]$ or 32.2 ft/sec^2

C_D = drag coefficient = $24/Re$ for $Re < 10^4$, [−]

N_{re} = Reynolds number = $Dq\gamma_w/\mu g$, [−]

D = particle diameter, [L] or ft

q, γ_w, μ are as previously defined

L = thickness of filter cake, [L] or ft

f = porosity, [−]

X = weight fraction of particles in a given size range, [−]

ϕ = a shape factor = $6V_p/DA_p$, [−]

V_p = particle volume, $[L^3]$ or ft^3

A_p = particle surface area, $[L^2]$ or ft^2.

Combining Eqs. (4) and (5) and solving for β as β_o for the case when $C_s = 0$ yields:

$$\beta_o = \left(\frac{(24)(1.067)}{10^6}\right)\left(\frac{\gamma_w}{\phi^2 \gamma_F f^4}\right) \Sigma \frac{X}{D^2} \qquad (6)$$

Figure 2 shows a typical particle size distribution for a filter aid such as diatomite or perlite. Two particle size distributions for idealized filter aids having the same effective size are superimposed on this curve. The idealized distributions are straight lines and define materials having uniformity coefficients of 1 and 6 respectively. Based on Eq. (6)

$$\beta_o = K \int_0^1 \frac{dX}{D^2} \qquad (7)$$

where K = a constant for filter aids having the same ϕ, γ_F, and f.

Table 4 gives the value of β_o for filter aids having the same effective size but different uniformity coefficients ranging between the minimum and maximum possible values for straight line distributions. For uniformity coefficients of 2.0 to 3.5, the mean value of β_o is $(1.35 \pm 0.45)(K/D_{10}^2)$, a variation of 33%.

The effective size of the filter aid in a filter cake can, therefore, on the basis of Eq. (7), be computed using an experimentally determined value of β_o:

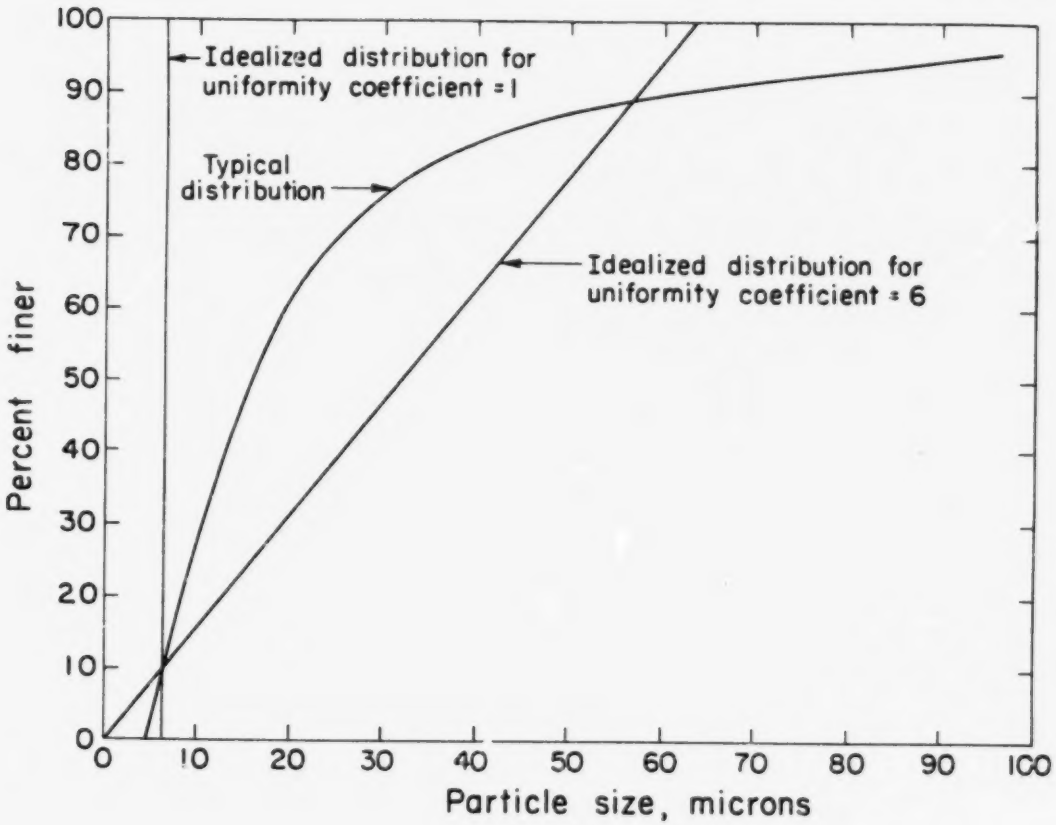

Fig. 2. Typical particle size distribution and two idealized particle size distributions for filter aids having the same effective size.

$$\beta_o = \left(\frac{(24)(1.067)(1.35)}{10^6}\right)\left(\frac{\gamma_W}{\gamma_F f^4}\right)\left(\frac{1}{\phi^2 D_{10}^2}\right) \tag{8}$$

where $$f = \left(1 - \frac{\gamma_F}{\gamma_W \rho_F}\right). \tag{9}$$

Figure 3 is a nomograph that can be used to calculate the porosity of a filter aid using Eq. (9). Thus,

$$D_e = \phi D_{10} = \frac{(5.88 \times 10^{-3})}{(1 - \gamma / \gamma_W \rho_F)^2} \left(\frac{\gamma_W}{\beta_o \gamma_F}\right)^{\frac{1}{2}} \tag{10}$$

Table 4. β_o values for filter aids having a straight line, particle size distribution for uniformity coefficients ranging from 1.0 to 6.0.

Uniformity coefficient	β_o, ft^{-2} (a)
1.0	$1.00\ K/D_{10}^2$
1.5	$0.58\ K/D_{10}^2$
2.0	$0.89\ K/D_{10}^2$
2.5	$1.16\ K/D_{10}^2$
3.0	$1.45\ K/D_{10}^2$
3.5	$1.82\ K/D_{10}^2$
4.0	$2.34\ K/D_{10}^2$
4.5	$3.20\ K/D_{10}^2$
5.0	$4.88\ K/D_{10}^2$
5.5	$9.89\ K/D_{10}^2$
6.0	∞

(a) D_{10} = effective size of filter aid, [L], ft

where D_e = the effective size indicated by the permeameter test, [L] or ft.

For determining the effective size in microns, the equation converts to

$$D_{em} = \frac{(1794)(\gamma_W/\beta_o\gamma_F)^{\frac{1}{2}}}{(1 - \gamma_F/\gamma_W\rho_F)^2} \qquad (10a)$$

or

$$D_{em} = \frac{1794\ (\gamma_W/\beta_o\gamma_F)^{\frac{1}{2}}}{f^2} \ . \qquad (10b)$$

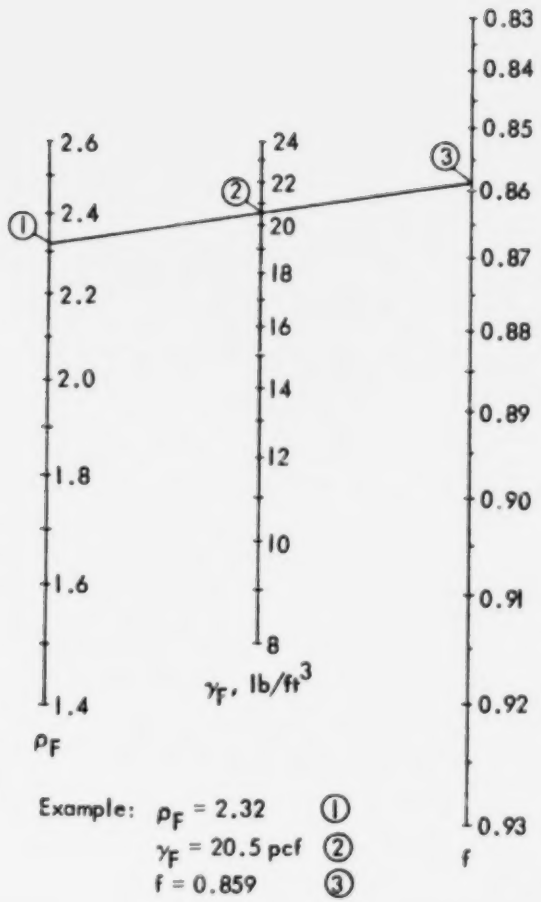

Fig. 3. Nomograph for calculating porosity (f) based on the equation: $f = (1 - \gamma_F/\gamma_W\rho_F)$.

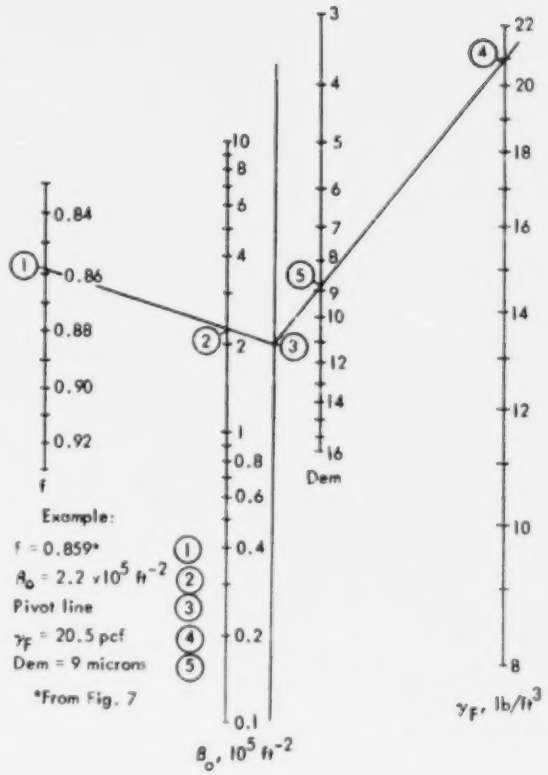

Fig. 4. Nomograph for calculating effective particle size (D_{em}) based on the equation:

$$D_{em} = \frac{1794\ (\gamma_W/\gamma_F\rho_F)^{\frac{1}{2}}}{f^2}\ .$$

Figure 4 is a nomograph that can be used to calculate the effective size in microns of a filter aid using Eq. (10b). Table 5 lists the average values of the effective sizes of the filter aids evaluated in this study.

Table 5. Average values of the effective size of the filter aids evaluated in this study.

Filter aid grade	Effective size		
	Permeameter[a] method, μ	Hydrometer method, μ	Coulter Counter method, μ
S2	8.6	–	10
S3	6.8	–	9
S4	6.1	–	9
J4	12.7	10	–
J3	12.4	7	–
J0	9.8	6	–
E6	16.4	11	–
E5	12.7	9	–
E2	10.8	8	–
G4	12.7	7	–
G1	8.8	5	–

(a) The calculated values for the effective size by the permeameter method have not been rounded off because they are used as the basis for a calculation referred to in Table 7.

Filter Cake Resistance with Suspended Solids

The results of the filtration tests are subject to several different kinds of interpretation. For example, the typical operating conditions and filtration results obtained using a single filter aid (J0, lot 1) are summarized in Table 6.

Figure 5 is a plot of log β vs log (C_S/C_F). The lower limit of β is shown as a horizontal line at $\beta = 2.27 \times 10^5$ ft^{-2}, the average value

Table 6. Summary of filtration test results[1],Part I for filter aid J0, lot 1.

Run number	C_S, ppm	C_F, ppm	C_S/C_F	β, ft^{-2}
159	8.08	296.0	0.027	2.03×10^7
160	8.11	228.9	0.035	3.27×10^7
161	8.25	378.0	0.022	1.23×10^7
162	8.27	454.2	0.018	0.92×10^7
163	8.22	170.0	0.048	5.65×10^7

of β_o for J0, lot 1. The upper limit of β is shown as a norizontal line at $\beta = 12.6 \times 10^9$ ft^{-2}. This is the value of β for a precipitate of hydrated ferric oxide precipitated from a solution of ferric chloride and determined using the constant-pressure filter. In the filtration tests, the resistance of the cake was related to the ratio of the concentration of suspended solids to body feed by an equation of the following form:

$$\beta = 10^a \left(\frac{C_S}{C_F}\right)^b . \qquad (11)$$

This form of presentation is a convenient way of relating the results of filtration tests made using a given grade of filter aid. Figure 6 is a plot of log β vs log (C_S/C_F) based on the mean values for the filter aids[1],Part I. Using this equation, different values for exponents a and b were determined for each filter aid. An effort was made to relate these exponents to the physical properties of the filter aids.

Further analysis of the relationships embodied in Eq. (4) and the shape of Fig. 6 revealed that the denominator in the fraction (C_S/C_F)

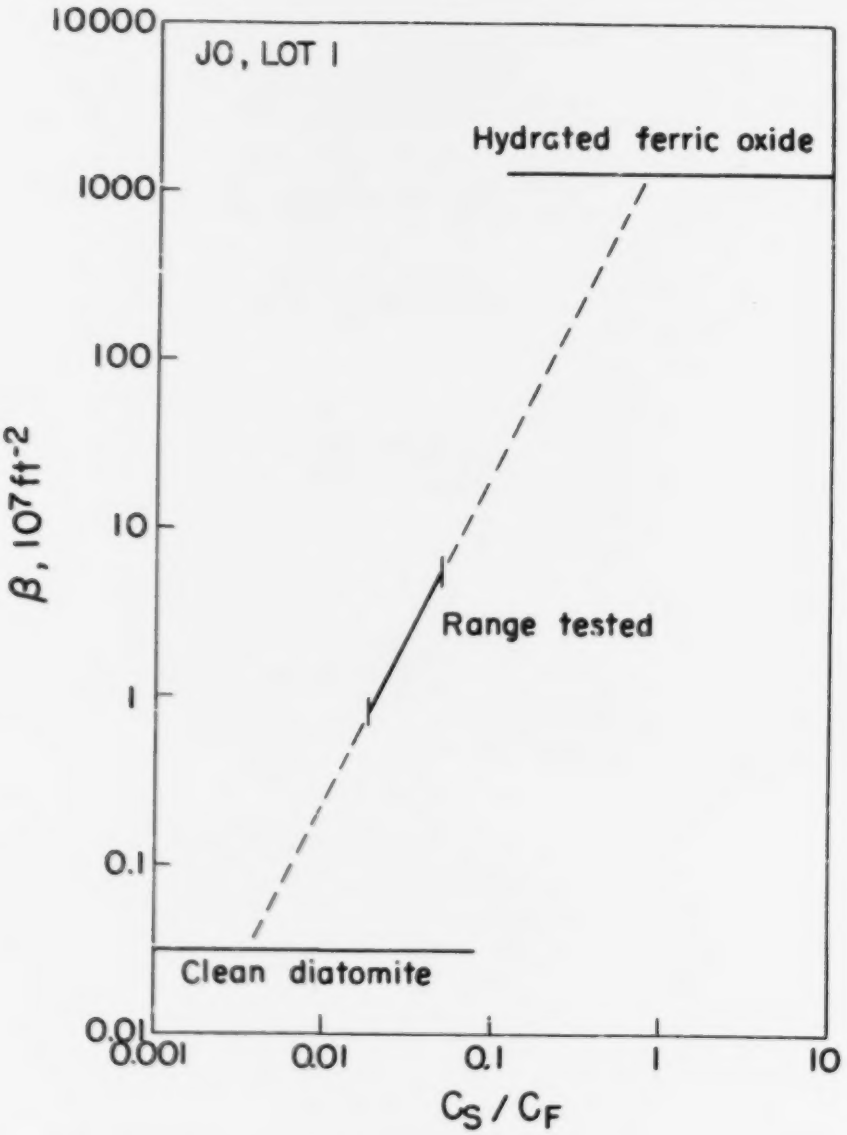

Fig. 5. Limiting values of β, using JO, lot 1.

is really a function of the void volume in the cake; hence, (C_S/C_F) should be replaced by (C_S/V_V) where V_V is the void volume. In retrospect then, a more logical way of relating the cake resistance to the cake characteristics would be using an equation of the following form:

$$\beta = 10^a \left(\frac{C_S}{V_V}\right)^b \qquad (11a)$$

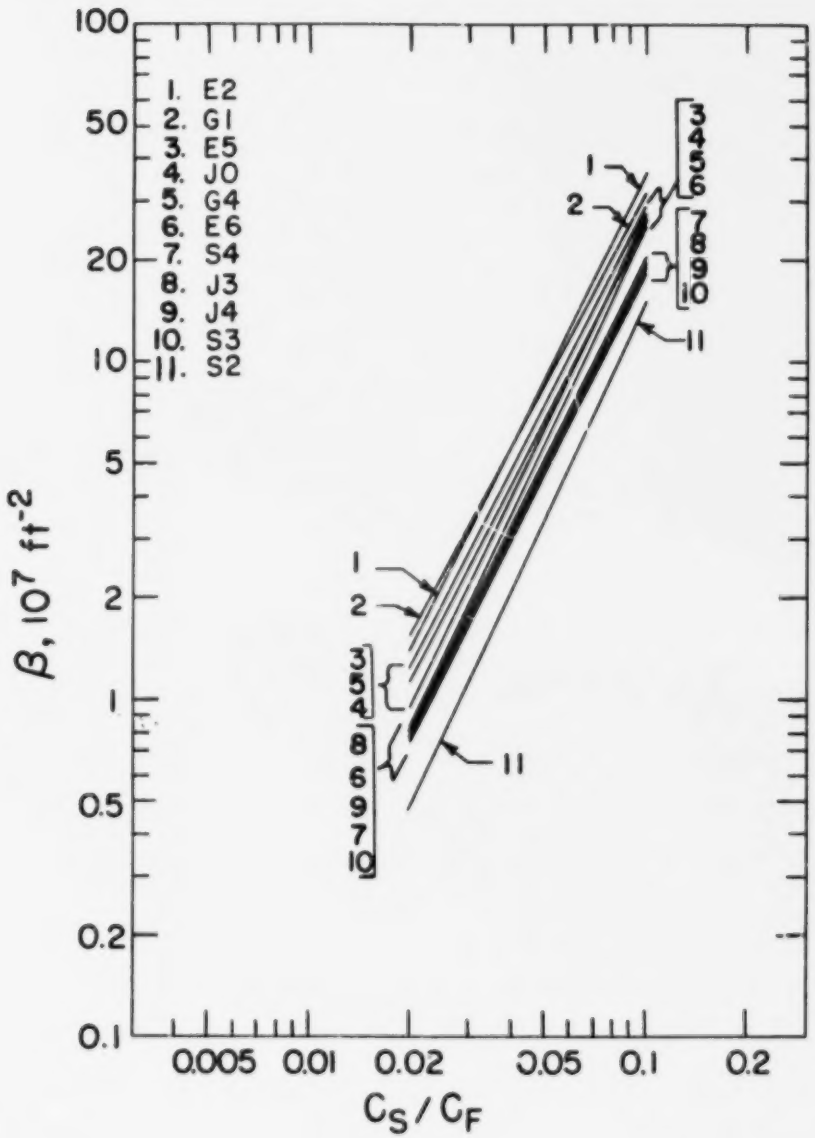

Fig. 6. Average relation of β and (C_S/C_F) values for 11 filter aids evaluated in this study.

where: V_V = the volume of the voids in the filter cake, [$L^3/10^6F$] or cu ft/10^6 lb.

or

$$V_V = \left(\frac{C_F}{\gamma_F}\right)\left(1 - \frac{\gamma_F}{\gamma_W S_F}\right). \qquad (12)$$

The volume of voids per unit weight of filter aid, V_U, $[L^3/F]$, or cu ft/lb, is

$$V_U = \frac{(1 - \gamma_F/\gamma_W S_F)}{\gamma_F} . \qquad (13)$$

Thus,

$$V_V = C_F V_U . \qquad (14)$$

With this equation, it might be expected that all of the grades of diatomite from a single manufacturer would provide the same value of exponents a and b. Similarly, it might be expected that all of the perlite grades from the same manufacturer would provide single values of a and b representative of that material. Since the headloss, H_c, through a flat septum is expressed by Eq. (4), the total resistance is really measured by the value of βC_F. In other words, using flat septa the values of βC_F must be the same with all filter aids which give "equivalent performance" under the same filter operating conditions. For any given value of C_S, the ratio of (C_S/V_V) (the ratio of the weight of suspended solids per cubic foot of void volume) will be affected inversely by the rate of body feed, C_F. Thus, as body feed increases, the solids removed per cubic foot of voids decreases directly with an increase in body feed. The effect of doubling the body feed concentration is to halve the solids concentration per cubic foot of body feed. Thus, βC_F measures the resistance of the total body feed and it may be more reasonable to express resistance as:

$$\beta C_F = 10^a C_S^{\ b} V_V^{\ c} \quad . \tag{15}$$

The results obtained in this study indicate that the value of the exponent b is 2 and c is - 1 within the precision of the data. When C_S is equal to zero, however, βC_F must be equal to $\beta_o C_F$. Equation (15) can be modified to account for this:

$$\beta C_F = \beta_o C_F + \frac{k C_S^{\ 2}}{V_V} \quad . \tag{15a}$$

Thus, Eq. (15a) has the following form:

$$\beta C_F = \beta_o C_F + \alpha C_S^{\ 2} \tag{15b}$$

where $$\alpha = k/V_V = k/C_F V_U \quad . \tag{16}$$

Based on the filtration results given in Table 1, k was found to be a function of the effective particle size of the filter aids. A different k value-particle size relationship (Fig. 7) was found to be representative of the filter aids from each manufacturer:

$$k = \frac{8.7 \times 10^9}{D_{em}} \qquad \text{S2, S3 and S4} \tag{17a}$$

$$k = \frac{10.3 \times 10^9}{D_{em}} \qquad \text{J4, J3 and J0} \tag{17b}$$

$$k = \frac{14.5 \times 10^9}{D_{em}} \qquad \text{E6, E5 and E2} \tag{17c}$$

$$k = \frac{12.7 \times 10^9}{D_{em}} \qquad \text{G4 and G1.} \tag{17d}$$

The effective size (D_{em}) and the volume of voids per unit weight of filter aid (V_U) are useful parameters for comparing the filtration properties of diatomite and perlite filter aids. On the basis of these parameters, the filtration equation given as Eq. (4) can be rewritten as:

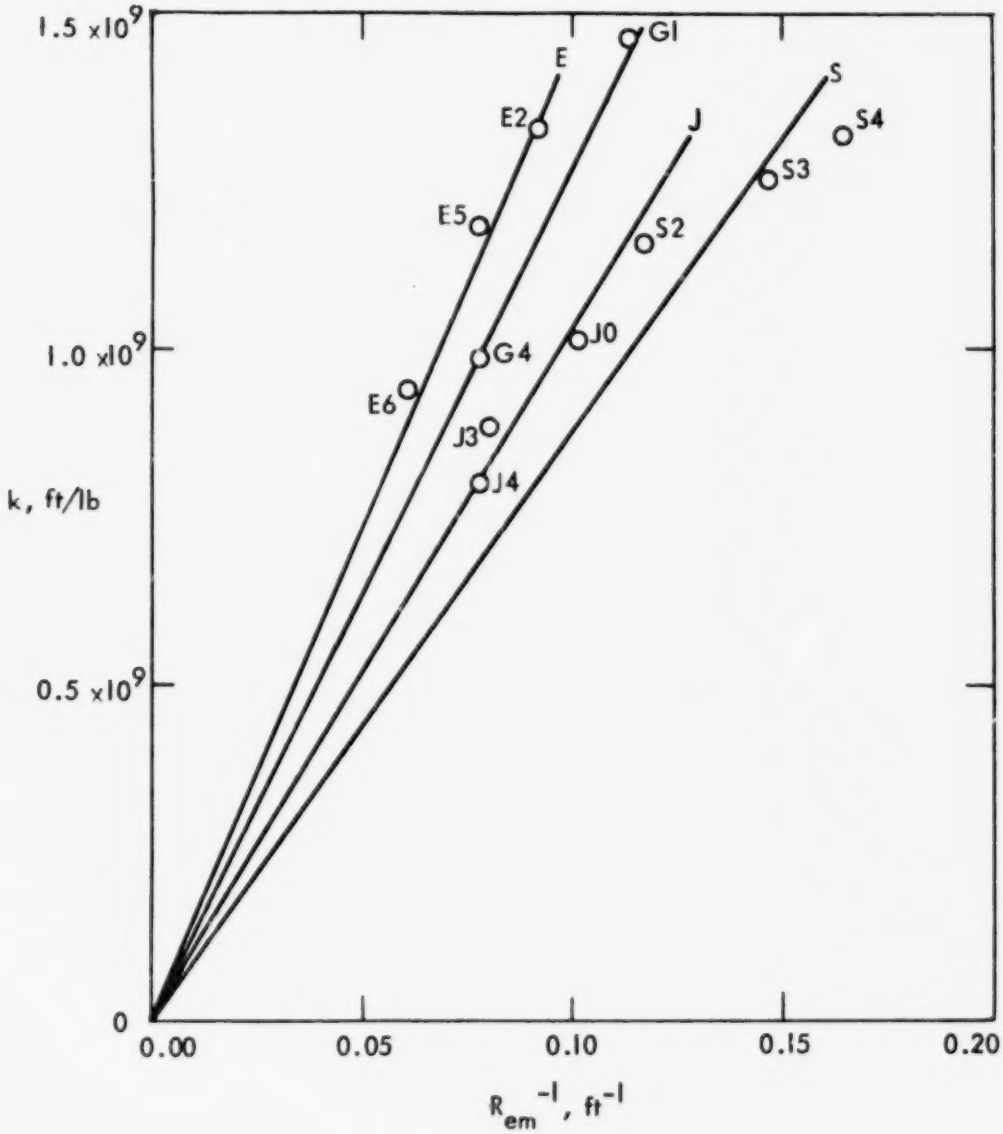

Fig. 7. Relation of k value to effective particle size of filter aids used in this study.

$$H_c = \left(\frac{q^2 t_H}{\gamma_W}\right) (\beta_o C_F + \alpha C_S^2) \qquad (18)$$

or as:

$$H_c = \left(\frac{q^2 t \mu}{\gamma_w}\right) \left[\beta_o C_F + \left(\frac{k}{V_U}\right)\left(\frac{C_S}{C_F}\right)^2\right]. \qquad (18a)$$

Equations (18) and (18a) can be interpreted as follows:

- For a given value of C_S, the headloss decreases with increasing concentrations of body feed as long as there is a significant fraction of suspended solids in the filter cake.
- When the fraction of suspended solids in the filter cake represents an insignificant amount, the headloss increases with increasing concentrations of body feed.
- The volume of voids per unit weight of filter aid, V_U, and the filter cake resistance, β_o, are useful parameters for predicting the filtration performance of a given filter aid when filtering the suspended solids carryover from an Erdlator solids contact unit in which ferric chloride is used as the coagulant (see Table 7).

Table 7. Prediction of body feed requirements for "equivalent performance"[(a)].

Filter aid grade	D_{em}, μ (Table 6)	V_U, cu ft per lb (Eq. (13))	k, ft per lb (Eq. (17))	V_F, cu ft per MG		% Finer
				Actual[(b)]	Predicted[(c)]	
S2	8.6	0.091	1.01×10^9	59.7	54.0	- 10
S3	6.8	0.071	1.28×10^9	68.2	69.0	1
S4	6.1	0.069	1.43×10^9	71.7	76.7	7
J4	12.7	0.044	0.81×10^9	44.9	45.0	0
J3	12.4	0.043	0.83×10^9	50.3	46.6	- 7
J0	9.8	0.043	1.05×10^9	55.7	59.0	6
E6	16.4	0.045	0.88×10^9	53.5	48.7	- 9
E5	12.7	0.036	1.14×10^9	62.6	65.7	5
E2	10.8	0.041	1.34×10^9	74.6	76.0	2
G4	12.7	0.036	1.00×10^9	56.8	56.9	0
G1	8.8	0.038	1.44×10^9	83.4	81.8	- 2

(a) Based on $q = 1$ gpm/ft^2, $t = 6$ hr, $H_c = 100$ ft of water, $C_S = 4$ ppm iron, water temperature = 20°C, flat septa.

(b) Table 1.

(c) Equation (18a) and $V_F = (8.33)C_F/\gamma_F$, $[L^3/L^3]$ or $[-]$ and the average physical properties given in Table 2.

Filter Aid Index

As may be seen in Table 7, the body feed requirements for a given manufacturer's filter aids can be predicted using the physical characteristics of the filter aids with a relatively small percentage of error with the aid of Eqs. (17a), (17b), (17c), and (17d). For the purposes of a filter

aid specification, however, one functional relationship, not four, is preferred. This end result was achieved by using the hydraulic radius in the relationship instead of the effective particle size.

The hydraulic radius of a conduit (or system of conduits) through which water is flowing is the ratio of the volume of the conduit filled with water to the area of the wetted walls. If the conduits are completely filled and the system of conduits consists of the space between spherical particles in a porous medium,

$$R = \frac{V_p}{A_p} \tag{19}$$

where R = hydraulic radius, $[L]$ or ft

V_p = volume of particle, $[L^3]$ or ft^3

$$= \frac{\pi D^3}{6} \left(\frac{f}{1 - f}\right) \tag{20}$$

and

A_p = area of particle, $[L^2]$ or ft^2

$$= \pi D^2 \tag{21}$$

where D = particle diameter, $[L]$ or ft

f = porosity, $[L^3/L^3]$ or $[-]$.

Therefore,

$$R = \frac{D}{6} \left(\frac{f}{1 - f}\right). \tag{22}$$

For nonspherical particles,

$$R = \frac{\phi D}{6} \left(\frac{f}{1 - f}\right) \tag{23}$$

where ϕ = a shape factor, $[-]$.

The porosity of a porous medium is related to the bulk density (γ_F) and the effective specific gravity (ρ_F) as follows:

$$f = (1 - \frac{\gamma_F}{\gamma_W \rho_F}). \tag{9}$$

Therefore,

$$R = \frac{\phi D}{6} (\frac{1 - \gamma_F/\gamma_W\rho_F}{\gamma_F/\gamma_W\rho_F}). \tag{24}$$

If the hydraulic radius is computed on the basis of the effective particle size (D_{10}),

$$Re = \frac{\phi D_{10}}{6} (\frac{1 - \gamma_F/\gamma_W\rho_F}{\gamma_F/\gamma_W\rho_F}). \tag{24a}$$

Since

$$D_e = \phi D_{10} = \frac{(5.88 \times 10^{-3})(\gamma_W/\beta_o\gamma_F)^{\frac{1}{2}}}{(1 - \gamma_F/\gamma_W\rho_F)^2} , \tag{10}$$

$$\begin{aligned} Re &= \frac{D_e}{6} (\frac{1 - \gamma_F/\gamma_W\rho_F}{\gamma_F/\gamma_W\rho_F}) \\ &= \frac{1}{6} \left[\frac{(5.88 \times 10^{-3})(\gamma_W/\beta_o\gamma_F)^{\frac{1}{2}}}{(1 - \gamma_F/\gamma_W\rho_F)^2} \right] (\frac{1 - \gamma_F/\gamma_W\rho_F}{\gamma_F/\gamma_W\rho_F}) \\ &= \frac{(5.88 \times 10^{-3}/6)(\gamma_W/\beta_o\gamma_F)^{\frac{1}{2}}}{(1 - \gamma_F/\gamma_W\rho_F)(\gamma_F/\gamma_W\rho_F)} \end{aligned} \tag{25}$$

If the hydraulic radius is expressed in microns (R_{em}), this equation becomes

$$R_{em} = \frac{298(\gamma_W/\beta_o\gamma_F)^{\frac{1}{2}}}{(1 - \gamma_F/\gamma_W\rho_F)(\gamma_F/\gamma_W\rho_F)} . \tag{25a}$$

The functional relationship between k and R_{em} for all of the filter aids tested was found to be (Fig. 8),

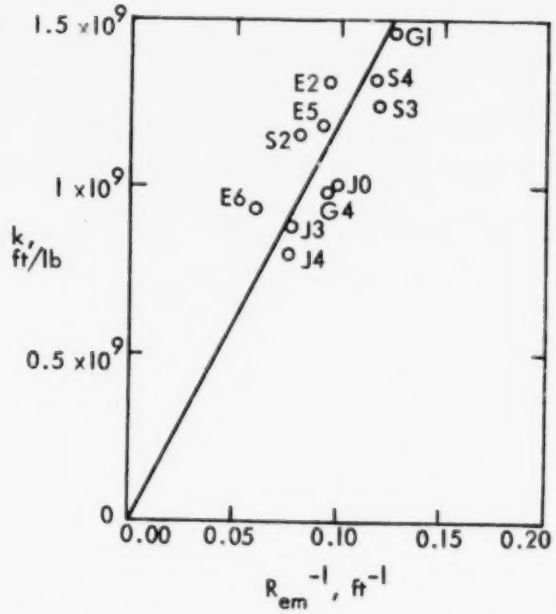

Fig. 8. Relation of k value to hydraulic radius of filter aids used in this study.

$$k = \frac{12.0 \times 10^9}{R_{em}} \qquad (17e)$$

Substituting this value for k into the filtration equation, Eq. (18a),

$$H_c = \frac{q^2 t\mu}{\gamma_W} \left(\beta_o C_F + \frac{12.0 \times 10^9}{R_{em} V_U} \frac{C_S^2}{C_F}\right). \qquad (18b)$$

The term $\beta_o C_F$ should be very small compared with the other term in the brackets for practical concentrations of C_F. If this term is eliminated and the equation is rewritten in terms of C_F:

$$C_F = \frac{q^2 t\mu (12.0 \times 10^9) C_S^2}{H_c \gamma_W R_{em} V_U} . \qquad (26)$$

$$V_F = \frac{C_F(8.33)}{\gamma_F} = \frac{q^2 t\mu (12.0 \times 10^9) C_S^2}{H_c \gamma_W R_{em} V_U} \left(\frac{8.33}{\gamma_F}\right). \qquad (27)$$

For the filtration conditions specified earlier,

$q = 1$ gpm/ft^2

$t = 6$ hr

$H_c = 100$ ft of water

$C_S = 4$ ppm iron

water temperature = 20°C, flat septa

$$V_F = \frac{579}{\gamma_F V_U R_{em}} . \qquad (27a)$$

Since

$$V_U = \frac{(1 - \gamma_F/\gamma_W\rho_F)}{\gamma_F} , \tag{13}$$

$$V_F = \frac{579}{(\gamma_F)\left[\frac{(1 - \gamma_F/\gamma_W\rho_F)}{\gamma_F}\right]R_{em}}$$

$$= \frac{579}{(1 - \gamma_F/\gamma_W\rho_F)R_{em}} , \tag{27b}$$

and

$$f = (1 - \frac{\gamma_F}{\gamma_W\rho_F}). \tag{9}$$

Therefore,

$$V_F = \frac{579}{f\ R_{em}} . \tag{27c}$$

According to Eq. (27c), the body feed requirement expressed on a volumetric basis is inversely proportional to the porosity and hydraulic radius of the filter aid used.

The porosity and hydraulic radius are both derived quantities based on physical properties of the filter aid:

$$f = (1 - \frac{\gamma_F}{\gamma_W\rho_F}) \tag{9}$$

$$R_{em} = \frac{(298)(\gamma_W/\beta_o\gamma_F)^{\frac{1}{2}}}{(1 - \gamma_F/\gamma_W\rho_F)(\gamma_F/\gamma_W\rho_F)} . \tag{25a}$$

If these terms are combined:

$$V_F = \frac{579}{(1 - \gamma_F/\gamma_W\rho_F)\left[\frac{(298)(\gamma_W/\beta_o\gamma_F)^{\frac{1}{2}}}{(1 - \gamma_F/\gamma_W\rho_F)(\gamma_F/\gamma_W\rho_F)}\right]}$$

$$= \left(\frac{579}{298\ \gamma_W^{3/2}}\right) \frac{\gamma_F^{3/2}\beta_o^{1/2}}{\rho_F}$$

$$= 3.95 \times 10^{-3}\ I \qquad (27d)$$

where I = filter aid index

$$= \frac{\gamma_F^{3/2}\beta_o^{1/2}}{\rho_F} \ . \qquad (28)$$

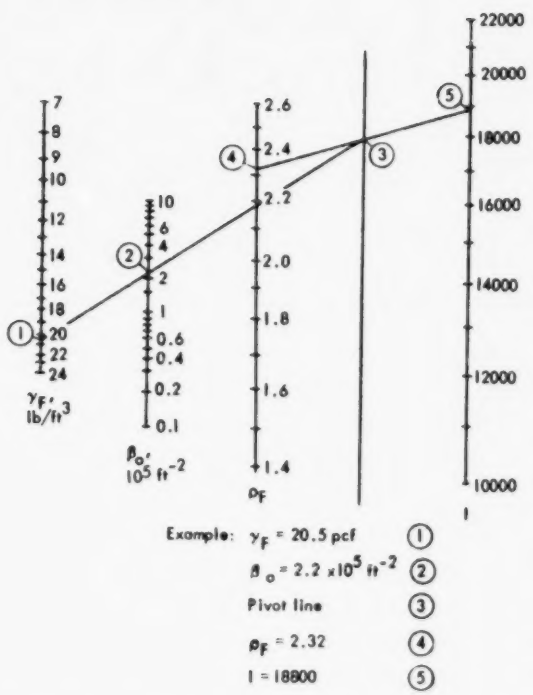

Fig. 9. Nomograph for calculating the filter aid index (I) based on the equation: $I = \gamma_F^{3/2}\beta_o^{1/2}/\rho_F$.

Figure 9 is a nomograph that can be used for calculating the filter aid index of a filter aid using Eq. (28). Equations (27d) and (28) and the physical characteristic data in Table 2 were used to predict the body feed requirements for "equivalent performance." The results are tabulated in Table 8. As may be seen by comparing the percent errors for the predictions in Table 8 with those in Table 7, the body feed requirements for all of the grades of filter aid can be predicted nearly as well using a single functional relationship as they can when a different functional relationship

Table 8. Filter aid index (I) and body feed requirement predictions for "equivalent performance"[a] for the eleven grades of filter aid tested in this study.

Filter aid grade	D_{em}, μ (Table 6)	I[b]	V_F, cu ft per MG		% error
			Actual[c]	Predicted[d]	
S2	8.6	12600	59.7	49.5	- 16
S3	6.8	19900	68.2	78.3	16
S4	6.1	18900	71.7	74.4	4
J4	12.7	12600	44.9	49.5	10
J3	12.4	13400	50.3	52.7	5
J0	9.8	16900	55.7	59.0	19
E6	16.4	15600	53.5	61.5	15
E5	12.7	16100	62.6	63.3	1
E2	10.8	16400	74.6	64.5	- 14
G4	12.7	16400	56.8	64.5	14
G1	8.8	21900	83.4	86.1	3

(a) Based on $q = 1$ gpm/ft^2, $t = 6$ hr, $H_c = 100$ ft of water, $C_s = 4$ ppm iron, water temperature = 20°C, flat septa.

(b) I, the filter aid index, was calculated using Eq. (28) and data for each filter aid from Table 2.

(c) Table 2.

(d) Equation (27c).

is used for each manufacturer's materials. The filter aid index should therefore provide a logical basis for characterizing the filtration properties of filter aids in a material specification.

Proposed Filter Aid Specification

A filter aid used on a volumetric basis and having characteristics similar to those of filter aid J3 could be specified by calling for "a filter aid having an effective size of 12.4 $\pm$ 6.0μ and a filter aid index of 13400 $\pm$ 3000." The filter aids accepted would have an "actual V_F" value ranging from 44.9 to 74.6 according to Table 8. The corresponding value for J3 is 50.3 cu ft per MG. Thus, to specify a filter aid with the filtration characteristics of J3, it would be necessary to accept some materials having filtration characteristics that would shorten the filter runs by as much as 30% (E2, for example).

Table 9 contains the ratings for all of the 36 lots of filter aid that were tested with the proposed standardized procedures for specific gravity, bulk density, and filter cake resistance. The table indicates that all lots tested of

- S2, J4, J3, and E6 were equal to or better than the specified material.
- S3, S4, and G1 were not acceptable on the basis of the specification.
- J0, E5, E2, and G4 were marginal — some lots would have been accepted and others would have been rejected.

Table 9. Ratings for 36 filter aid lots on the basis[a] of a filter aid index (I) of 13400 ± 3000 and an effective size (D_{em}) of 12.4 ± 6.0μ.

Filter aid grade	Lot number	ρ_F	γ_F pcf	β_o ft^{-2}	I	D_{em}	Rating[b]
S2	1	1.50	9.94	4.12×10^5	13400	8.8	A
	4	1.50	10.20	4.47×10^5	14500	8.4	A
	5	1.46	9.70	4.02×10^5	13100	9.0	A
	6	1.54	9.90	4.42×10^5	13400	8.4	A
	9	1.58	9.92	4.34×10^5	13000	8.4	A
	20	1.47	9.44	4.05×10^5	12500	9.0	A
	21	1.95	10.34	4.31×10^5	11200	8.0	A
S3	1	1.64	12.56	5.50×10^5	20100	7.0	R
	2	1.82	12.61	5.04×10^5	17500	7.1	R
	3	1.75	12.49	5.60×10^5	18800	6.7	R
	4	1.72	12.90	6.54×10^5	21800	6.3	R
S4	1	1.95	12.90	6.54×10^5	19200	6.1	R
	2	2.01	13.10	6.46×10^5	19000	6.1	R
J4	4	2.30	19.64	1.10×10^5	12800	12.9	A
	7	2.30	19.82	1.17×10^5	13100	12.5	A
J3	5	2.31	18.98	1.29×10^5	12900	12.0	A
	7	2.32	20.89	1.08×10^5	13500	12.9	A
J0	1	2.30	19.92	2.27×10^5	18500	9.0	R
	4	2.31	19.96	1.52×10^5	15000	11.0	A
E6	2	2.17	19.28	0.71×10^5	10400	16.6	A
	3	2.22	19.14	0.71×10^5	10100	16.4	B
	4	2.26	19.48	0.68×10^5	9900	16.5	B
E5	1	2.31	25.79	1.17×10^5	19400	12.0	R
	3	2.30	22.26	1.07×10^5	14900	12.8	A
	17	2.30	21.47	1.03×10^5	13900	13.2	A
E2	1	2.28	20.74	1.54×10^5	16300	10.9	A
	2	2.29	20.86	1.37×10^5	15400	11.5	A
	3	2.30	20.78	1.54×10^5	16200	10.8	A
	4	2.27	20.48	1.78×10^5	17200	10.2	R
G4	1	2.25	23.88	1.20×10^5	18000	12.2	R
	2	2.24	23.46	1.03×10^5	16300	13.2	A
	3	2.34	23.60	0.99×10^5	15400	13.2	A
	4	2.25	23.13	1.15×10^5	16800	12.4	R
	5	2.26	23.64	1.20×10^5	17600	12.1	R

Table 9. Continued.

Filter aid grade	Lot number	ρ_F	γ_F pcf	β_o ft^{-2}	I	D_{em}	Rating[b]
G1	2	2.32	22.24	2.58×10^5	23000	10.7	R
	3	2.24	22.34	1.99×10^5	21000	12.0	R

(a) J3 assumed to be the specified grade.

(b) Ratings: A accept
R reject
B better than specified grade.

CONCLUSIONS AND RECOMMENDATIONS

This study has shown that measurement and interpretation of several physical characteristics of a filter aid will provide a basis for characterizing the filtration properties of the filter aid. The significant characteristics are

- effective specific gravity, ρ_F
- clean filter cake resistance, β_o
- bulk density, γ_F.

Further, these properties can be used in comparing alternate choices of filter aids in establishing which are equivalent, superior, or inferior in terms of their ability to remove the suspended solids remaining in the effluent from an Erdlator with a minimum rate of headloss build up. These same properties can be used to exclude in a specification those filter aids that would be so fine that they would not be retained on the septum of a filter or so coarse that they would not obtain the desired quality of effluent.

The parameters recommended for use in classifying the filtration properties of the filter aids are

- Effective size (D_{em}), [L], in microns – this parameter may be calculated using either Eq. (10a) or Figs. 7 and 8 which are nomograph solutions for this equation.
- Filter aid index (I) – this may be calculated using either Eq. (28) or Fig. 9 which is a nomograph solution for this equipment.

ACKNOWLEDGMENTS

This work was supported by the Engineering Research Institute, Iowa State University, through funds made available by the U.S. Army Engineer Research and Development Laboratories through Research Contract DAAK02-67-C-0408 and in part by the Federal Water Pollution Control Administration through FWPCA Research Grant WP-00196, Research Fellowship 5-F1-WP-26, 104 (H. R. Bridges), and Graduate Training Grant 5T1-WP-45.

The authors also wish to acknowledge the assistance of John Shouse, Laboratory Technician, Jerry Huang, Graduate Research Assistant, Harold Bridges, FWPCA Research Fellow, Mandan Lal Arora, Graduate Research Assistant and all of the other students and hourly workers who assisted in the study.

REFERENCES

1. Baumann, E. R. and C. S. Oulman, Final Report on Filter Aid Specifications, Engineering Research Institute, Iowa State University, Ames, Iowa. (ERDL Contract DAAK 02-67-C-0408) ERI-269 (August 25, 1968).

   Part I. Filtration Characteristics of Several Commercial Filter Aids (E. R. Baumann, M. L. Arora, C. S. Oulman) ERI-217.

   Part II. Physical Properties of Several Commercial Filter Aids (C. S. Oulman, E. R. Baumann, John Shouse) ERI-267.

   Part III. Rationale for a Material Specification for Commercial Filter Aids for Military Use (C. S. Oulman, E. R. Baumann) ERI-268.

   Part IV. Determination of the Effective Specific Gravity, Bulk Density, and Filter Cake Resistance of Precoat Filter Aids (E. R. Baumann, C. S. Oulman) ERI-263.

   Part V. User Manual, Program for Determination of an Index of Filter Cake Resistance Using Filter Aid Filters, or the BID PROGRAM (Harold R. Bridges, E. R. Baumann) ERI-104.

   Part VI. User Manual for MAIDS PROGRAM, Program for Determination of Beta-Prediction Equations by Manipulation and Interpretation of Data Systems (Harold R. Bridges, E. R. Baumann) ERI-116.

2. Baumann, E. R. and C. S. Oulman, Interim Report on Filter Aid Specifications, Engineering Research Institute, Iowa State University, Ames, Iowa (ERDL Contract DAAK 02-67-C-0408) ERI-164 (April, 1968).

   Part I. Filter Aid Specification (E. R. Baumann, C. S. Oulman).

   Part II. Determination of Effective Specific-Gravity of Filter Aids (E. R. Baumann, C. S. Oulman, John Shouse).

   Part III. Determination of Bulk Density and Filter Cake Resistance of Precoat Filter Aids (C. S. Oulman, E. R. Baumann).

3. Hazen, Allen, "Annual Report of the Massachusetts State Board of Health" (1892). Reference cited in Fair, Gordon M. and John C. Geyer, Water Supply and Waste Water Disposal (John Wiley and Sons, Inc. N.Y., 1954, p. 665).

4. Clark, John W. and Warren Viessman, Jr., Water Supply and Pollution Control (International Textbook, Scranton, Penn., p. 302-304. 1965).

APPENDIX

The following sample calculations are provided to illustrate the use of the equations that serve as a basis for the proposed filter aid specification. Assume that the standardized procedures proposed in Part IV of this report yielded the following results for a given filter aid:

$$\rho_F = 2.32$$

$$\gamma_F = 20.51 \text{ pcf}$$

$$\beta_o = 2.22 \times 10^5 \text{ ft}^{-2}.$$

The proposed specification is based on the effective particle size (D_{em}) and the filter aid index (I) of the filter aid. The effective size is specified so as to exclude filter aids that would be too fine grained to deposit on the septa. The filter aid index is used to limit the acceptable grades to those that would provide approximately the same rate of headloss build up. The equations used in calculating D_{em} and I are:

$$D_{em} = \frac{1794(\gamma_W/\beta_o\gamma_F)^{\frac{1}{2}}}{f^2} \qquad (10b)$$

where D_{em} = effective particle size based on permeameter test, [L] in microns,

γ_W = density of water, $[FL^{-3}]$ or 62.4 pcf,

β_o = filter cake resistance of clean filter aid, $[L^{-2}]$ or ft^{-2},

γ_F = bulk density of filter aid, $[FL^{-3}]$ or pcf,

f = porosity or void ratio, [−],

$$= (1 - \gamma_F/\gamma_W\rho_F) \qquad (9)$$

where ρ_F = effective specific gravity, $[FL^{-3}/FL^{-3}]$ or [−]

and

$$I = \frac{\gamma_F^{3/2} \beta_o^{1/2}}{\rho_F} \quad . \tag{28}$$

Substituting into Eq. (9)

$$f = 1 - \frac{(20.51 \text{ pcf})}{(62.4 \text{ pcf})(2.32)}$$

$$= 1 - 0.142$$

$$= 0.858.$$

Figure 3 is a nomograph that can be used to calculate the porosity of a filter aid. The nomograph is used in the following way:

- Locate the value of ρ_F on the left hand scale (① $\rho_F = 2.32$).
- Locate the value of γ_F on the middle scale (② $\gamma_F = 20.5$ pcf).
- Connect points ① and ② with a straight line and extend the line to intersect the right hand scale ③. The porosity is the value given by the intersection of the construction line and the right hand scale:

  $f = 0.859$

If Eq. (10b) is used to calculate the effective size:

$$D_{em} = \frac{(1794)\left[(62.4)/(20.51)(2.22 \times 10^5)\right]^{\frac{1}{2}}}{(0.859)^2}$$

$$= \frac{(1794)(1.37 \times 10^{-5})^{\frac{1}{2}}}{(0.739)}$$

$$= \frac{(1794)(3.70 \times 10^{-3})}{(0.739)}$$

$$= 9.0\mu.$$

Note: This equation will be rational only if the units for γ_W and γ_F are the same (e.g., pcf) and β_o is expressed in ft^{-2}.

Figure 4 is a nomograph that can be used to calculate the effective particle size of a filter aid. The nomograph is used in the following way:

- Locate the value of f on the left hand scale (① f = 0.859).
- Locate the value of β_o on the second scale (② $\beta_o = 2.2 \times 10^5$ ft^{-2}).
- Connect points ① and ② with a straight line and extend the line to intersect the pivot line ③.
- Locate the value of γ_F on the right hand scale (④ γ_F = 20.5 pcf).
- Connect the points ③ and ④ with a straight line. The effective size (D_{em}) ⑤ is the value given by the intersection of the second construction line and the scale for D_{em}:

$$D_{em} = 9.0\mu.$$

Equation (28) is used to calculate the filter aid index as follows:

$$I = \frac{(20.51)^{3/2}(2.22 \times 10^5)^{1/2}}{(2.32)}$$

$$= \frac{(92.9)(4.71 \times 10^3)}{2.32}$$

$$= 18{,}860.$$

Note: The units used in this equation must be pcf for γ_F and ft^{-2} for β_o.

Figure 9 is a nomograph that can be used to calculate the filter aid index of a filter aid. The nomograph is used in the following way.

- Locate the value of γ_F on the left hand scale (① γ_F = 20.5 pcf).
- Locate the value of β_o on the second scale (② $\beta_o = 2.2 \times 10^5$ ft^{-2}.
- Connect points ① and ② with a straight line and extend the line to intersect the pivot line ③.
- Locate the value of ρ_F on the center scale (④ ρ_F = 2.32).

- Connect points ③ and ④ with a straight line and extend the line to intersect the right hand scale ⑤. The filter aid index is the value given by the construction line and the right hand scale:

  I = 18,800.